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Research paper



Effect of Aluminium closed-plate on energy absorption of hat-section tubes

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Abstract

The hat-section tubes are a typical steel profile used in many structural applications. Among metals, steels are strong and excellently tough, but relatively heavy. The objective of this study is to investigate the possibility and generate design information on the uniaxial bending, impact, and energy absorption characteristics of hat-section tube with combination of lighter material. In this project, aluminium plate was used as a closed-plate to replace the relatively heavy mild steel plate. Finite element (FE) models were developed using ABAQUS and validated through experiment. Parametric studies were conducted mainly for investigating the dynamic impact response of the combined-material tubes. Present works were also compared with existing results of conventional tubes in order to demonstrate their workability. Results show that the use of alum closed-plate is a promising option for lighter hat-section tube while maintaining its strength and functionality. This was assured in comparison with conventional ones. In addition, wall thickness remains the most influential factor that affects crashworthiness characteristics of ductile materials in particular.

Keywords: *Energy absorption, Hat-section, Specific energy absorption, Impact bending*.

1. Introduction

Thin-walled structural components have been used widely in many applications from automotive, aeronautics, and civilian structures to the gigantic structures like the ship hull. For energy absorbing application, they are chosen for their exceptional advantages in crashworthiness and lightweight [1-5]. On the other hand, environmental issue is always a major concern with regard to the higher fuel consumption due to the vehicle's weight. However, without further investigation, excessive weight reduction in structure could lead to a more serious problem which is safety [6, 7]. Therefore a standard for vehicles prior to sale or service must be established. Some of the criteria may also cover the environmental issue as well as safety aspects are concerned. Under European Directive 2003/102/CE, every new car is required to pass some test protocols including the crash test to ensure every safety aspect is taken care (https://osha.europa.eu).

For decades, car makers have been struggling for lighter vehicles in order to improve the fuel consumption which is one of the policies set in many countries. This could be achieved by replacing or associating steel parts by lighter metals such as aluminium and magnesium or by polymer composites. Most metal structures fail under impact through buckling and/or folding that involve extensive plastic deformation. They are highly in ductility compared to composites which are mostly brittle and less deformable. Failure in composites starts at the micro-scale, with matrix micro-cracking and fiber break which is less elongation. It is obvious that for structural or energy absorbing application, the ductile response is better compared to brittle which has less deformation against load.

In the mean time, new problems were discovered due to the introduction of new materials such as the suitability of joining techniques. Spot welding is the most used technique for metal sheet assembly including the hat-section tubes. It works effectively with steel based material but not with others, whether it is composite or hybrid. Alternatively, joining process can be done using mechanical joints such as screws, rivets, and clinch joints. In recent years, study on structural adhesive is increasing and many reports show promising results for actual application [8, 9]. It is so versatile that almost any kind of material can be bonded including those with complex design where other method could not reach. The adhesive layer provides continuous joint for additional insulation as well as protection of internal parts against contamination. Flexural tests of hat-section tubes of different combination (i.e. Metallic, Composite, and Hybrid = Metal + Composite) showed great potential for all type of combination. In terms of specific energy absorption (SEA), the hybrid hat-section tubes possess the highest value compared to other combinations. Despite all these advantages, this technology has its drawbacks. Firstly, the residual stress that induced due to the varying thermal expansion coefficient between adhesive and adherent. Secondly is the relatively long curing time which depends on type of adhesive, however much has been improved even some have reached excellent reticulation time. The other option is by associating other mechanical fasteners with adhesive [10].

Wall thickness has a major influence on the energy absorbed. Thicker wall has more material for plastic deformation, which means more energy can be absorbed. However, the SEA may react in opposite way since the thicker wall comes with heavier mass. The High Strength Steel (HSS) which is a type of alloy steel can provide better mechanical properties at the same wall thickness as

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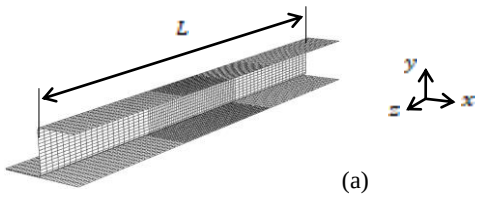
typical carbon steel. Impact bending test on a set of hat-section tubes made of HSS has indicated that the potential of utilizing the HSS in reducing the total weight of automotive structure was convincing [11]. However, use of HSS may require additional cost since the material itself is expensive.

Plan for replacing steel with lighter materials has long been studying by many of automakers. Among ductile materials, aluminium and magnesium are highly desirable and this includes newly developed material such as composites and foams. Recovery target of 85% of end-of-life vehicles has driven makers to adopt lightweight materials technology which could enhance recycability without compromising the safety aspect. In addition, new rules and regulations for higher decarbonized electricity grids would result in high use of aluminium in cars [12]. Meanwhile, development of new material at lower cost with improved stiffness and strength would enable application in high-volume to ensure the sustainability of this industry.

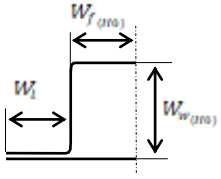
Conventional design of hat-section tube is still relevant today. Even though the profile remains the same, the material used and its combination have evolved towards minimum weight. It seems that no attempt has been made to integrate steel and aluminum plates in the fabrication of hat-section tubes. The objective of this study is twofold: to develop FE model of steel-alum hat-section tubes and to study the impact response through varying some of the parameters. Firstly, the impact response of hat-section tubes with aluminum closed-plate is investigated. Quasi-static and impact three-point bending tests were conducted to validate the FE models. Parametric studies were performed to study the effect of different parameters such as wall thickness, web width, and impact speed on load-deflection, Energy Absorbed (EA), and Specific Energy Absorption (SEA). Comparison with conventional hat-section tubes was also made in order to demonstrate the potential and workability under different conditions. In general, hat-section tubes with aluminum closed-plate shows fairly similar trend with conventional hat-sections which indicates potential application. This study will generate new research information and design guideline for the use of steel-alum hat-section tubes.

2. Method

In this work, the finite element model of the conventional hat-section tube is adapted from [13]. Simulations are performed using explicit finite element code, ABAQUS, and the preliminary simulations show that, the deformation mode of full, half, and quarter models can be treated symmetrically. Simpler FE model can reduce the number of degrees of freedom (DOFs) and computational time. Fig. 1 shows cross section geometry of halfly meshed FE model of hat-section tube. Table 1 lists some of the cross section dimensions of the tube and Fig. 2 shows cross sectional dimension of the tube in a full meshed model under three-point bending.



(a)

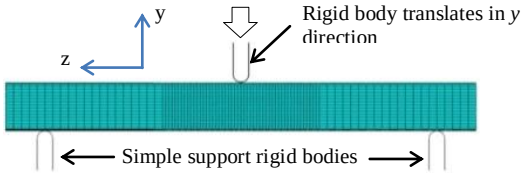


(b)

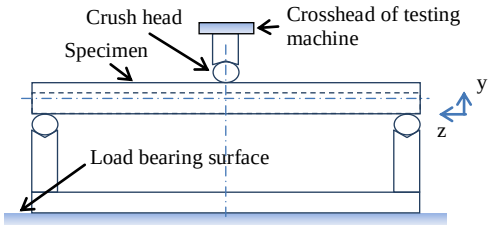
Fig.1: (a) Meshed and (b) cross section geometry of half model hat-section tube

Table 1 : Beam and its cross sectional dimension (Unit: mm)

No. of specimen		Part dimension (mm)	
Quasi-static	Impact	Hat-section	Closed-plate
2	2		
Web ($W_{w(H0)}$)		30	-
Flange ($W_{f(H0)}$)		60	-
Lip (W_l)		30	-
Width (W)		-	120
Length (L)		-	300
Thickness (t)		1	1



(a)



(b)

Fig. 2: (a) Meshed and (b) full model of tube under point bending

Coupon tensile tests in accordance with AS1391-1991 are conducted and Fig. 3 shows the true stress-strain results for both mild steel and aluminum. Table 2 tabulates some of the selected points for used in the FE models. The strain rate effect is taken into account with respect to dynamic loading using overstress power law as used in the previous studies [13, 14]. Parameter values in the power law equation are different for both mild steel and aluminum and incorporated into the FE model accordingly.

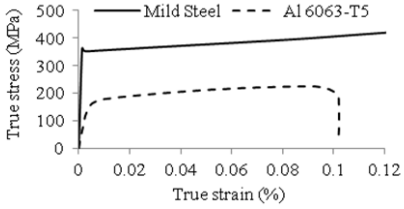


Fig. 3: True stress-strain curve from tensile test for mild steel and Al 6063-T5

Table 2 : Material properties of hat-section tube

	Material	
	Mild steel	Al 6063-T5
Density (kg/m³)	7809	2700
Ultimate Tensile Strength (MPa)	391	220
Yield strength (MPa)	340	173
Young's modulus (GPa)	200	65
Poisson's ratio	0.3	0.33

3. Results and discussion

All simulation results are based on quarter model. Fig. 4(a) and (b) show the comparison of FE model and experiment. The experiment replicates the FE model with mild steel plate used as the open hat-section and Al plate as the closed-plate. The mean-load curve is plotted using MATLAB based on the load-deflection curve data. Both FE and experiment results indicate similar pattern with steep rise during the initial crush then decreases gradually before leveling off. Simulation and experiment are broadly similar corresponds to area under the curves with average difference within 5%. Next, Fig. 5(a) and (b) are referred. The experimental result shows that dynamic load resisted by the beam initially increases rapidly until it reaches the first local maximum value before de-

creasing and then rapidly increasing to the second local maximum value as shown in Fig. 5(a). This could be possibly due to the effect of impact vibration followed by the subsequent collapse of the flanges and webs which caused fluctuation of measured loads. The general trend though for impact and quasi-static loading is quite similar but in terms of load value, impact loading exhibits approximately 15% higher than quasi-static value due to the change in momentum. The impact simulation tails off earlier while experiencing slight spring back effect from specimen. The maximum measured depth was about 43 mm when some areas of the beam reach their yield points and permanent deformation occurs. The overall difference between model and measured output was approximately 8%. The comparison was made according to the area difference under the curves. The FE model agrees well with the actual deformation as depicted in Fig. 6.

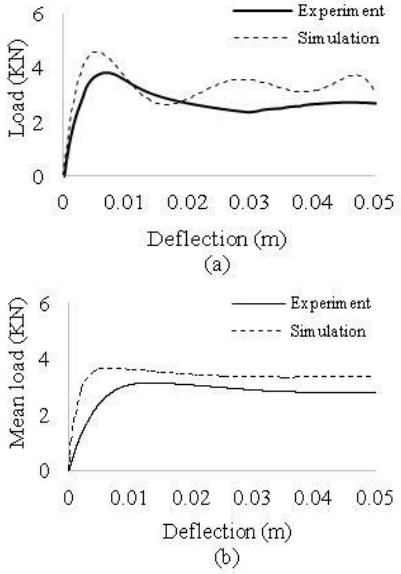


Fig. 4: Quasi-static three point bending (a) load-deflection and (b) mean load-deflection

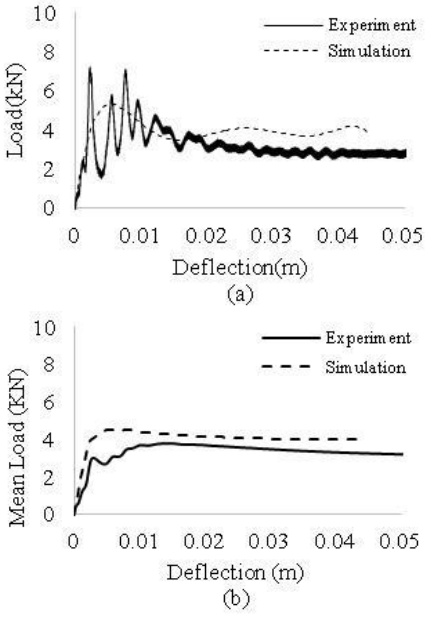
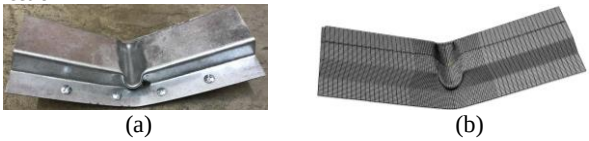


Fig. 5: Impact three point bending (a) load-deflection and (b) mean load-deflection



(a) (b)

Fig. 6: Collapse mode for impact test (a) experiment and (b) simulation

An impact loading is considered a dynamic loading when its velocity reaches 10 m/s or beyond [15]. During this stage the inertia force becomes prominent due to the high velocity. In this work, three different impact velocities were chosen (5 m/s, 10 m/s, and 15 m/s) and the impact responses under each condition were recorded. Fig. 7 illustrates comparison of the effect of impact velocity on the load-deflection response for mild steel closed-plate (conventional) and aluminum closed-plate hat-section tubes at constant wall thickness of 3 mm. Each curve in the figure is plotted to the maximum deflection which is the distance where the beams rest after the impact. The mean load and initial peak load for both type of closed-plate have considerably increased under dynamic loading with varying impact velocity.

In addition to this, the impact velocity under dynamic loading seems to have great effect on the initial peak loads compared with quasi-static loading for both type of tubes. Basically, the hinge movement of the rigid tubes' blocks plus the lateral movement or buckling of the indented sidewalls at the instant of impact due to the presence of lateral inertia effects are presumed to the differences in the initial peak load. Furthermore, strain rate sensitivity is another factor to be considered since the hat channels are made from low carbon steel which causes an increase of the flow stress for higher impact velocities. As can be seen, even though the amount of energy absorbed by conventional hat-section is slightly larger, it does not affect the opponent. In terms of percentage of elongation, the aluminium closed-plate increases compared to conventional, however, was fractionally declined for every increment in speed (~40%, ~16%, and ~9%). Longer impact duration with almost similar absorbed energy provides more cushioning effect for a more forgiving impact. All these indicate suitability of aluminium as a new option for the closed-plate.

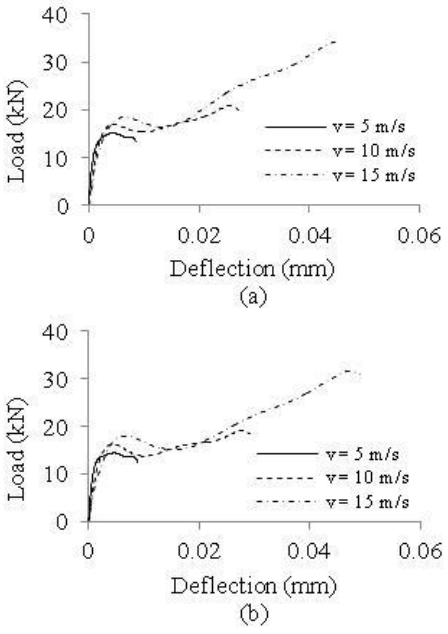


Fig. 7: Comparison of the effect of impact velocity on the load-deflection response of (a) conventional and (b) Al closed-plate hat-section tubes (t_{MS} = t_{Al} = 3 mm, m = 36 kg)

Fig. 8 illustrates the effect of varying aluminum wall thickness on load-deflection response and energy absorbed at constant velocity. As the wall thickness increases, the load starts to deviate significantly after its first drop as seen in Fig. 8(a). It seems that, the role of closed-plate starts to take effect at this point. Even though thicker wall thickness contains more material for plastic deformation, no significant change is observed in terms of energy absorbed capacity as shown in Fig. 8(b). Another possible cause could be that lateral inertia forces increase as the wall thickens, thus increase the stiffness of the tubes. Therefore, at constant velocity, thicker closed-plate may have lesser deformation. The SEA, also called the Energy Absorbed (EA) per unit mass is given as:

$$SEA = EA/m \quad (kJ/kg) \qquad (1)$$

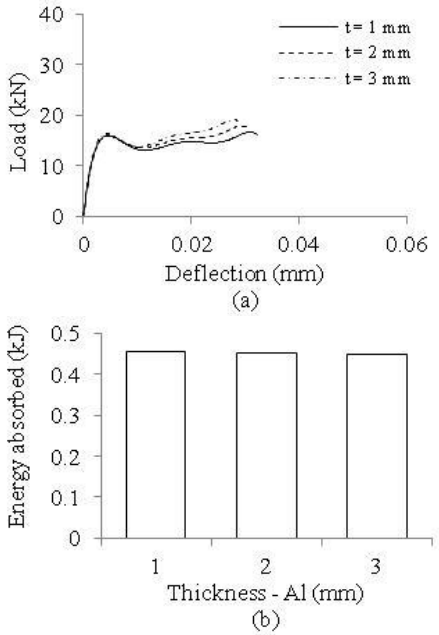
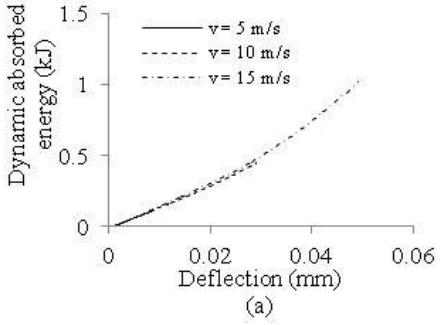


Fig. 8: Effect of varying Al wall thickness on load-deflection response and energy absorbed (v = 10 m/s, t_{MS} = 3 mm)

In general, the energy absorption capacity of thin-walled energy absorbers increases as the impact velocity increases. Similar studies show that the response is parallel as found in hat-section tubes made of high strength steel (HSS) and aluminium square tubes subject to impact loading [11]. Increasing the impact velocity increases the initial peak load as can be seen in Fig. 7 and the associated mean load as well as absorbed energy would also increase. Fig. 9(a) shows the effect of varying impact velocity on the dynamic absorbed energy at constant wall thickness. As anticipated, the inertia effects due to the high impact speed seem to have increased the crush load and amount of energy absorbed compared to quasi-static loading as also observed in previous established studies [16]. In general, the EA increases as the impact velocity increases. Fig. 9(b) shows the effect of varying impact velocity on SEA. At constant mass, the SEA increases by almost triple and double at 10 and 15 m/s respectively. This result is comparable to the existing conventional hat-section tubes and therefore indicates its potential [5].

Fig. 10(a) shows the effect of varying Al closed-plate thickness on SEA from 1 mm to 3 mm at constant speed and wall thickness. The SEAs gradually decrease by approximately 7% for every 1 mm increase in thickness due to the additional material that comes with extra weight. Fig. 10(b) shows the effect of varying web width on SEA from 20 mm to 40 mm at constant speed and wall thickness. This time the SEAs increase by approximately 19% and 7.5% for every 10 mm increase in web width. As the mass in the web increases nonlinearly, the SEAs also increase.



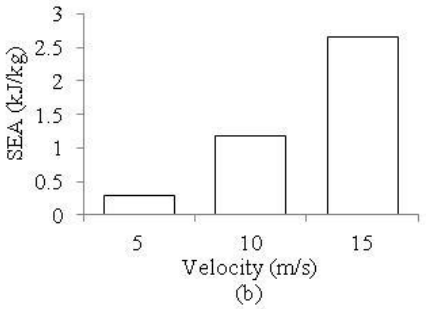


Fig. 9: Effect of varying impact velocity on the dynamic absorbed energy and SEA (t_{MS}=1 mm, t_{Al}=2 mm)

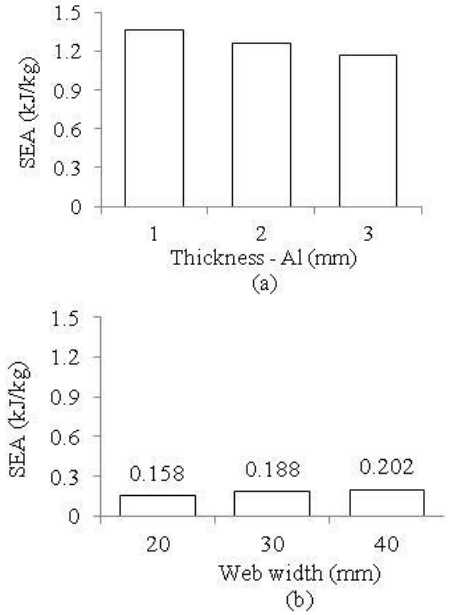


Fig. 10: Effect of varying (a) wall thickness and (b) web width on the SEA (t_{MS} = 3 mm, v = 10 m/s, span = 150 mm & t_{MS} = t_{Al} = 1 mm, v = 3 m/s, span = 200 mm)

4. Conclusion

Dynamic impact bending of hat-section tubes with aluminium closed-plate is studied in the present work. Quasi-static and dynamic three-point bending tests were performed and the FE models were adequately validated. Computational parametric studies were carried out to observe the response pattern in comparison to conventional hat-section tubes and to investigate the effect of some different parameters under dynamic loads. Based on existing results, the response patterns of the modified hat-section tubes are fairly similar to the conventional. Modified tubes are little bit lower in terms of total EA due to the higher ductility of aluminium than steel. However, aluminium closed-plate provides lower inertia effect for a better cushion during post impact. Varied wall thicknesses of aluminium closed-plate have insignificant effect on the EA. This is in contrary to the thicker wall in hat channel that contributes most in the total EA. Two controlling parameters which could affect the SEA are wall thickness and web width. Under constant velocity, increasing the wall thickness has resulted in decrement of SEA due to the increasing in mass. However, tubes with wider web width response the other way around in tandem with minimal increase in mass.

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